Scenario Development for the Integrated Control in Freeway Ramp Junction

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ABSTRACT

More than 280 interchanges in South Korea have been operated. The interchanges are where the surface street system and the freeway system are connected with a ramp and needed to be controlled efficiently. The operation at ramp-freeway junction is complicated and becomes worse year after year owing to difficulty of dealing with two different systems and traffic characteristics. In South Korea, the queue spillback on ramp often occurs in peak time periods and causes heavy congestion at the traffic merging points. To lessen the traffic congestion at freeway ramp junction, the possible alternatives and strategies in operation and control are needed. This paper introduces the operation scenarios for integrating the control system between arterial and freeway. The system requirements and functions are introduced and operational scenarios are briefly proposed. To show the importance of geometry characteristics, acceleration lane was considered as factor impacting the operation quality. To illustrate the impact of operation scenario, the simulation study was performed and evaluated with ramp metering strategy.

1. INTRODUCTION

Traffic operation at ramp-freeway junctions becomes more important in freeway system where an acceleration lane is generally used to connect the entrance ramp with freeway. A merging process is required at the entrance ramp junction since vehicles from a ramp enter an acceleration lane, and then move into a freeway after finding an acceptable gap. Vehicles' merging movements on an entrance ramp to the freeway traffic often reduce vehicle speeds on the freeway and easily cause traffic congestions. It is expected that differences of acceleration lanes in length and type bring about some operational change in the junction area.

In Korea, more interchanges and junctions are constructed to overcome weak accessibility of freeway, but their abrupt increase in the quantity leads to traffic problems such as recurrent traffic congestions, and more accidents over the areas. In general, interchanges and junctions are the most typical conflict areas where drivers weave vehicles to exit or enter freeway system. More than 280 interchanges are operated in Korea and the operation quality at ramp-freeway junction becomes worse year after year. In the metropolitan areas, the queue spillbacks on ramp areas often occur in peak time periods and cause heavy congestions at merging areas.

To lessen the traffic congestion at ramp-freeway junction, the possible alternatives in operation and control were tried in Korea. One of them was the use of the ramp metering system. In 1997, the ramp metering system was first installed at twelve entrance ramps on an urban expressway in Seoul City, Korea. However, none of drivers wanted to stop at the entrance ramp for the signal. In the field test, the signal violation rate of ramp metering was too high to operate the system. It was found that the use of ramp metering system was not successful in Korea, even though many previous studies in the world reported that the ramp metering was helpful to improve freeway operations. As another alterative to improve the operations, the dynamic operation methodology of the acceleration lane was proposed. This approach was suggested because the acceleration lanes on freeway were too long to be operated successfully, especially in rush hours. It may be a challenging approach to mitigate the traffic congestion.

This paper introduces the operation scenarios for integrating the control system between arterial and freeway. The system requirements and functions are introduced and operational scenarios are briefly proposed. To show the importance of geometry characteristics, acceleration lane was considered as factor impacting the operation quality. To illustrate the impact of operation scenario, the simulation study was performed and evaluated with ramp metering strategy.

2. RAMP METERING AND ACCELERATION LANE CONTROL

Ramp metering is not a very new traffic management concept. Various forms of ramp metering have been used widely. It is categorized into the four groups: pre-timed metering strategies, traffic-responsive metering strategies, coordinated ramp metering strategies, and other strategies. Pre-timed metering strategies are to determine the metering rates at off-line, based on the normal daily demand pattern and estimated freeway capacity. Wattleworth (1963) developed a ramp metering model using a linear programming method. Papageorgiou (1980) suggested an linear programming model that deals with congested situations. Lovell and Daganzo (2000) modified Wattleworth’s model to include time-dependency.

Traffic-response metering strategies are to determine the suitable metering rates, based on real time traffic data including freeway speed, volume, and occupancy. They include the demand-capacity strategy, the occupancy strategy, and the ALINEA strategy. Masher et al. (1975) attempted to control the ramp flow to fully utilize the downstream freeway capacity. Papageorgiou et al. (1991) developed a closed-loop ramp metering strategy, ALINEA. Diakaki and Papageorgiou (1994)

suggested METALINE, which is a extended version of ALINEA.

The coordinated metering strategies used a sophisticated macroscopic traffic flow model that is combined with an optimal approach to determine ramp metering rates. Payne (1979) developed the FREFLO model to simulate freeway traffic flow. Ross (1988) modified Payne's model with a new formulation that assumes that the free-flow speed is a constant and traffic density is independent. Integrating the optimal control model with the macroscopic traffic flow models resulted in large-scale, nonlinear optimization problems. The Linear-quadratic (LQ) feedback strategy is one of the most commonly studied methods within the automatic control theory. It linearizes the nonlinear model equations around a certain value and uses a quadratic penalty function to control deviation from the target value. Yuan and Kreer (1971) proposed this LQ model and many researchers suggested the extended LQ models.

The optimal ramp metering strategies were proposed and evaluated. Zhang and Levinson (2004) formulated an optimal ramp control with real time data. Chen et al. (1990) proposed a fuzzy logic controller for a ramp metering in a situation of incident. The rule-based expert systems and artificial neural networks were also used for determining the suitable metering rates (Papageorgiou et al. (1995), Zhang(1997)).

The length of the acceleration lane has significant effect on merging operations. Short lanes provide on-ramp vehicles with restricted opportunity to accelerate before merging. The result is that most acceleration must take place on the mainline, which disturbs through vehicles. Short acceleration lanes also force many vehicles to slow significantly and even stop while seeking an appropriate gap in the Lane 1 traffic stream. According to the AASHTO, the length of acceleration lane is determined by the design speed on freeway and ramp roadway. The distance required for acceleration in advance of this point of convergence is governed by the speed differential between the average running speed on the entrance curve of the ramp and the running speed of freeway. In case of freeway condition with 100 km/h of design speed on freeway and 60km/h of ramp roadway, the acceleration lane excluding transition section must be over 220m and it must be over 1.2 times on two lane-ramp roadway.

Kim (1997) estimated available merging capacity and distance of acceleration from entrance ramp to freeway. Drew et al. (1968) studied the determination of merging capacity drop at the entrance ramp. Shin (1997) developed speed prediction models for freeway merging area. He validated that the length of acceleration lane is one of important variables. The longer the length of acceleration is, the less through traffic volume is under traffic congestion. Wenquan et al. (2005) conducted a field study to model vehicle's merging behavior from an acceleration lane to freeway traffic.

Little references were found on how the long acceleration lane has effects on the traffic operation. The long acceleration lane was constructed with the hope that longer acceleration lane will improve the merging capacity at interchange in Korea. Many acceleration lanes were constructed with extremely long length of about 1,000 meters. Intuitively, it is anticipated that longer

acceleration lane will help vehicles to merge more comfortably. Long acceleration lanes provide on-ramp vehicles with more opportunity to accelerate before merging under normal traffic conditions. However, as the traffic becomes more congested, they will cause severe traffic problems. This research is focused on the dynamic operation of long acceleration lane. As an alternative to mitigate the traffic congestion, the dynamic operation methodology for the long acceleration lane was tested using a microscopic simulation model and was validated in the field.

3. SCENARIO DESIGN FOR THE SYSTEM INTEGRATION

Freeway and arterial networks are often subject to unrestrained demands significantly greater than available capacity. Capacity is often reduced at bottleneck locations such as major interchanges and bridges. There is a lack of integrated operational strategies and procedures that focus on maximizing the effectiveness of the entire corridor. This paper proposes a systematic approach to control the freeway and arterial networks. The system will be developed in the smart highway project as shown in Figure 1.

A. Overview of Freeway Corridor System Integration

Operationally, there is a lack of specific knowledge concerning how operational strategies can be utilized to support effective coordinated corridor operations. Operational scenarios such as signal timing coordination in conjunction with ramp metering are required. Other strategies that coordinate freeway, arterial, and transit operations also need to be studied. The strategies of a variable speed limit in conjunction with a ramp metering setting and signal timing plan on the adjacent arterials are very effective to mitigate the traffic congestion in freeway.

Operational integration includes operational strategies such as ramp meters, advanced traffic control, variable speed signs, and lane controls. The integrated system should be designed to implement the various operational strategies. The integrated control system should control the traffic flows at freeway and arterial in responding to incidents occurring on the freeway mainline under various traffic and geographic conditions.

To accomplish this goal, the proposed system should have the following functions:

- **Monitoring and estimating the evolution of traffic states over the corridor networks including the arterial**. The traffic variables include density, speed, flow rate, and queue lengths, which can be measured from detector data in a surveillance system. Especially, the queue lengths on arterial and on-ramp should be controlled effectively to improve the entire networks. The function should be able to predict the time-varying traffic flow propagation along the freeway and arterial network.
- **Operating with optimal control strategies under the operational constrains**. The control model should be formulated for non-recurrent congestion, with realistic operational

constraints due to a lane composition and signal parameters. In this process the objective function to evaluate the whole system should be defined.

- **Providing viable control decisions with an efficient algorithm**. There are many efficient algorithms for controlling the components of the network. In the Smart Highway project, a relevant algorithm will be developed and used for providing control decision.
- **Integrating a feedback mechanism**. Because the traffic flow has a stochastic nature and driver behavior is various, the parameters for the control model are needed to be various over time. Therefore, the control system should incorporate a feedback mechanism to respond instantly the traffic state in freeway and arterial networks. In this process the control decisions are updated in a timely manner.
- **Providing measurements of effectiveness for evaluating the control strategies**. This function is to evaluate the integrated system and take necessary actions. The function should be able to evaluate the network performance for freeway and arterial networks individually.

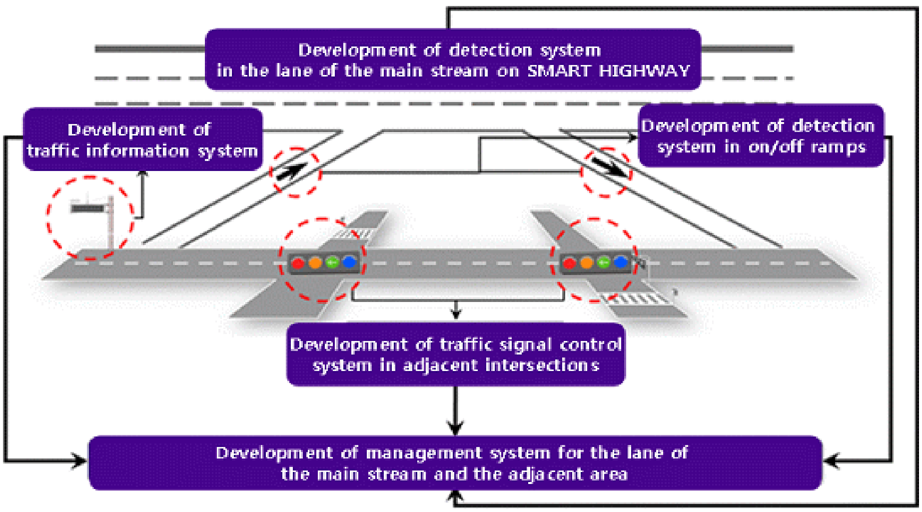


Figure 1. Concept of System Development

B. Required System Inputs

The integrated control system is operated based on the following three types of input data.

Traffic Information

- Time and location of the queues that has occurred
- Freeway mainline and ramp capacity
- Potential duration of queues in arterial and ramp
- Time-varying traffic demand patterns for the corridor and arterial network, including freeway and arterial volumes, intersection turning rates, and on-ramp entering rates

System Operation Parameters

- Phase sequences and constant clearance time
- Common cycle length for all intersections for better performance.
- Minimum and maximum allowable values for the control parameters such as diversion rate, metering rates, and cycle length
- Time and location of the queues that has occurred
- Freeway mainline and ramp capacity

Route Choice

- Selection principle for selecting diversion rates at critical off-ramps, and maintaining on-ramp metering rates, and diversion rates at adjacent intersections
- Provision of route information to the drivers stopping at intersections to enter on ramp

C. Design of Operation Scenarios

For the smart highway project, the possible operation scenarios are proposed for the integrated system operation. Each operational scenario can be operated individually and sometimes it can be operated jointly.

- Ramp metering of fixed, or traffic-responsive type for a local interchange, which is systematically connected to the main center for smart highway corridor
- Ramp metering incorporated with a variable speed limit in the freeway at the merging point
- Traffic signal control at an intersection to improve the ramp traffic flow, but ramp metering is not integrated into the ramp metering
- Ramp control for providing the emergency vehicles with operational priorities so that they can access the freeway mainline safely
- Integrated network control for ramp metering and signal control

4. IMPACT OF OPERATION SCENARIO

The above mentioned operation scenarios are affected by the type of interchange, length of acceleration lane, number of ramp lane, and so on. In this paper, the acceleration lane is also proposed as an important factor to be considered when we design a system. A simulation study was performed to show the impact of the scenario. In this simulation study, the impacts of length of acceleration lane, and ramp metering were tested.

A. CORSIM Highway Simulation Model

CORSIM is a combination of two micro-simulation models: the arterial network microscopic simulation model NETSIM and the freeway microscopic simulation model. The highway micro-simulation module of CORSIM is based on the FRESIM model which is in turn derived from the INTRAS model developed in the late 1970s. The CORSIM car-following model for freeway traffic

micro-simulation, FRESIM, is based on the INTRAS car-following algorithm and uses the PITT car-following model. The basic assumption of FRESIM is that a following vehicle will try to maintain a space headway between simulated vehicles. In FRESIM, ten different driver types can be modeled according to the level of driving aggressiveness. The driver sensitivity parameter determines the average headway in heavy traffic conditions and therefore it also defines maximum lane capacity. In the FRESIM car-following model, a driver's reaction time is used to model driver's reaction mechanism. The other important parameter is the gap acceptance that control driver's aggressiveness. For the implementation, a version of TSIS 5.0 was used and specific details on the version may be found elsewhere.

B. Simulation Modeling and Implementation

To test the effects of acceleration lane, the test site for the modeling and implementation was the entrance ramp at the interchange in Kyoungbu Freeway, Korea. It has three lanes on mainline and a single entrance ramp. To evaluate the effects of acceleration lane length, each lane of 500, 700, and 900m was chosen for the study. As shown in Table 1, the test condition at the site was represented, which easily yields congestion nearby the ramp roadway. The free flow speeds of freeway and entrance ramp are 55mph and 35mph, respectively. Also, the ratio of heavy vehicle was set to 10%.

Table 1. Condition of Freeway and Entrance Ramp

	Number of lanes	Average Volume	Level of Service
Mainline	3	5,000	E~F
On-Ramp	1	1,200	C~D

To test the effects of ramp metering, a network was coded into CORSIM as shown in Figure 2 and simulation was performed with the following signal parameters at intersection shown in Table 2. ALENEA algorithm was used for the test.

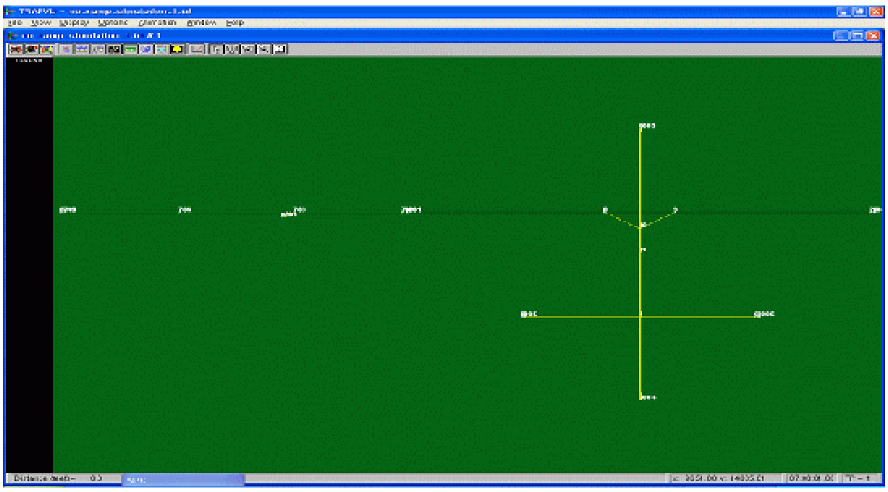
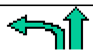
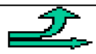


Figure 2. CORSIM Ramp Metering

Table 2. Signal Parameter at Intersection

Phase				
Green	25	20	25	20
Yellow	3	3	3	3

To examine the influence of the shortening of acceleration lane length, it was necessary to model properly the operation of the flexible length of acceleration lane. An accident was created at the time when the running speed on the ramp is higher than the speed on the freeway. The location of intentionally planned accident was supposed to be at 2/3 of the acceleration lane. Once an accident occurs, the downstream lane section of the acceleration lane is supposed to be closed, which is equal to the restricted use of acceleration lane in dynamic operation with no rubber-necking effect. Drivers' personality in CORSIM was set to be relatively aggressive by adjusting the car-following parameters and the driver's aggressiveness factor while holding the other parameters to their default values.

C. Simulation Results

A preliminary study was performed to evaluate how the operation with flexible length of acceleration lane affects on the mainline section and the merging section. Table 3 represents the input volume scenario for the freeway and the ramp.

Table 3. Input Volume Profile

(vph)

	8:00~ 8:15	8:15~ 8:30	8:30~ 8:45	8:45~ 9:00	9:00~ 9:15	9:15~ 9:30	9:30~ 9:45
Mainline	4,800	5,400	5,400	4,800	4,800	4,400	4,400
Ramp	1,200	1,300	1,300	1,000	1,000	700	700

Table 4 presents the simulation results for the three acceleration lanes. First of all, the mitigation starting time to shorten the length of acceleration lane was determined when running speed on the ramp is higher than that of freeway mainline. As shown in Table 2, seven time periods were tested from 8:00 a.m. to 9:45 a.m. with the input scenario volume. For each acceleration lane of 500, 700, and 900m, the time period of speed reversion between the ramp and the freeway mainline was identified. Simulation results showed that the length of acceleration lane during congestion period is relatively effective in term of total vehicle-mile, total vehicle-hour, and average speed.

Table 4. Effectiveness Comparison by Length of Acceleration Lanes

		MOE	Status Quo	Dynamic Control
500m	Results	total vehicle-miles	27,949.36	27,944.10
		total vehicle-hours	863.76	846.09
		avg. speed(mph)	32.36	33.03
		move time/total	0.60	0.61
	Reference	Time period of speed reversion ⇒ 8:45~9:00 Initial time to shorten length of acceleration lane ⇒ 8:30 Available distance of acceleration ⇒ 360m Unavailable distance of acceleration ⇒ 140m		
700m	Results	total vehicle-miles	28,051.48	28,132.55
		total vehicle-hours	1,126.04	1,025.88
		avg. speed(mph)	24.91	27.42
		move time/total	0.46	0.51
	Reference	Time period of speeds reversion ⇒ 8:30~8:45 Initial time to shorten length of acceleration lane ⇒ 8:15 Available distance of acceleration ⇒ 450m Unavailable distance of acceleration ⇒ 250m		
900m	Results	total vehicle-miles	28,051.20	28,139.24
		total vehicle-hours	1,082.07	1,013.46
		avg. speed(mph)	25.92	27.77
		move time/total	0.48	0.52
	Reference	Time period of speeds reversion ⇒ 8:45~9:00 Initial time to shorten length of acceleration lane ⇒ 8:30 Available distance of acceleration ⇒ 600m Unavailable distance of acceleration ⇒ 400m		

To evaluate the performance of ramp metering, average queue time, average queue length, maximum queue length, and average stop time were collected. Table 5 and 6 represent the simulation results for the ramp metering. Table 6 shows that the ramp metering strategy is relatively effective in term of total vehicle-mile, delay time, move time, and average speed.

Table 5. Link Performance Comparison of Metering and No Metering Strategy

MOE	Link	average queue time (sec)	average queue length (veh)	maximum queue length (veh)	average stop time (sec)
No Metering	Main line Link Arterial Link	2551.2 11131.8	25 110	160 135	2505.6 10338.3
Metering	Main line Link Arterial Link	1132.8 1110.8	8 111	78 140	1115.4 10395.2

Table 6. Network Performance Comparison of Metering and No Metering Strategy

Network Performance	No Ramp Metering	Ramp Metering
Total vehicle-mile	31,496	29,755
Delay time(vehicle-hour)	634.3	614.52
Move time(vehicle-hour)	706.69	671.36
Average speed(mph)	23.49	23.14

5. CONCLUDING REMARKS

The research was performed to develop the integrated control system for freeway and arterial network. A brief concept of the integrated system was proposed, and system function and requirement are also presented. To illustrate of the impact of operational scenario, ramp metering system was used as an example. Also, geometric characteristics are important factors in operation. The road conditions of extremely long acceleration lane are common at interchanges and junctions in Korea. The length and type of acceleration lane affect the driver’s behavior and freeway operation. In this paper, simulation study showed that acceleration lane has impacts on the freeway mainline operation and ramp metering strategy is relatively effective.

The conceptual architecture of the proposed integrated control system will be developed in the third year of the smart highway project with the strategic, systematic, and functional requirements. The system requirements will be defined in detail and then system functionality will be designed with operation strategies. Various operation strategies and algorithms are also developed and evaluated using microscopic simulation model in the project.

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